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Description and Performance Characteristics of a Captive Airfoil Balloon System Used in the Initial Phase of the Aeropalynologic Survey Project

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Abstract

The purpose of this paper is to present results of a system analysis and operational evaluation of a captive airfoil balloon system. The system was used operationally in support of an Aeropalynologic Survey Project at NASA Wallops Island, Virginia, during the summer of 1966.

I. BACKGROUND

The project requirements included the need for a system capable of lifting itself and a payload up to and including an altitude of 1,000 ft, remaining aloft for a one-week period, and capable of returning usable data to the ground. The short time increment between request and need for a lifting system did not permit specification, procurement, and evaluation of a new system. However, an available balloon system, operationally employed by the local Environmental Science Services Administration personnel, was used.

2. GENERAL DESCRIPTION

The subject system, referred to as a Kytoon, is an airfoil balloon which is sustained aloft by both aerostatic and aerodynamic forces. The Kytoon, which is manufactured by Dewey and Almy Company, is a four-finned airship consisting of a nylon casing, muslin tail fin assembly, nylon harness, rubberized shock cord, and a neoprene bladder, the latter serving as the gas envelope (Reference 4). The Kytoon is a symmetrical airfoil in the form of a body of revolution which is circular in cross section and elliptical along its longitudinal axis, the curve of which is given by

$$y = 0.6696 + 0.7132x - 0.0823x^2$$

where

y = the ordinate from the centerline and
x = the abscissa along the centerline.

The preceding equation was determined by the Method of Least Squares for Curve Fitting which was programmed into the GE-625 digital computer at Wallops Station, Virginia. The properties of the Kytoon are given in Table 1.

3. DETAILED DESCRIPTION AND PHYSICAL CHARACTERISTICS

The Kytoon, shown in Figures 1, 2, and 3, is 9.25 ft in length and has a maximum diameter of 4.350 ft, giving it a fineness ratio of 2.11. Its noninflatable fins, which are in a cruciform arrangement, have an area of 4.87 sq ft per fin. The bridle system consists of two sections of 170-lb test braided nylon line, one section of bungee shock cord and two brass harness couplings, one of which acts as the attach point for the tether line. Figures 1 and 3 show the arrangement of the bridle system in a tethered flight condition. It should be noted that by adjustments to the rigging of the bridle system, the point of attachment and conditions for equilibrium are changed.

Since the Kytoon is a nonrigid airship, its shape depends on the pressure of the lifting gas contained in the gas envelope. In addition to the loss of buoyancy, a decrease of the pressure inside the gas envelope will cause the Kytoon to become limp. Several gases which are lighter than air include coal gas, hydrogen, and helium. Due to the dangers involved and the nonavailability of the first two gases mentioned, helium was used to inflate the Kytoon. The properties of air and helium are given in Tables 2 and 3.

Table 1. Properties of Kytoon

Length	ft	9.25
Maximum diameter	ft	4.350
Fineness ratio		2.11
Volume	ft^3	87.791
F_B at 1A at sea level	lb	6.705
Weight	lb	3.1
Usable free lift	lb	2.134
Number of fins at 90° spacing		4
Area of each fin	ft^2	4.87
C_D		See Figure 6
C_L		See Figure 6
α	deg	7.5
β	deg	0
Permeability to helium per 24 hr	% usable free lift	15
Static efficiency $\frac{L_S}{F_B}$	%	32
Break strength	lb	160
Weight per 1,000 ft	lb	1.28
Spring constant at 95 lb tension and initial length of 10 ft	lb/ft	47.5
Stretch of 10-ft length after 95 lb tension is applied and released	%	1.58
Material	Nylon	
Type of construction	Braided	

Table 2. Properties of Air

Molecular weight		29
R	ft/°R	53.3
ρ at sea level	slugs/ft^3	$(2.377)10^{-3}$
ρ at 1,000 ft	slugs/ft^3	$(2.308)10^{-3}$
μ at sea level	lb/sec/ft^2	$(.38)10^{-6}$
μ at 1,000 ft	lb/sec/ft^2	$(.371)10^{-6}$
γ at sea level	lb/ft^3	0.07647
γ at 1,000 ft	lb/ft^3	0.07428
P at sea level	psi	14.69
P at 1,000 ft	psi	14.17
T at sea level	°R	519
T at 1,000 ft	°R	515.4

Table 3. Properties of Helium

Molecular weight		4
R	ft/°R	386
μ at 68°F	lb/sec/ft^2	0.0411
ρ at sea level	slug/ft^3	0.003276
γ at sea level*	lb/ft^3	01066
γ at 1,000 ft*	lb/ft^3	01036
P at sea level*	psi	14.834
P at 1,000 ft*	psi	14.314
T at sea level*	°R	519
T at 1,000 ft*	°R	515.4
He unit lift at 1A at sea level	lb/ft^3	0.062
He unit lift at 100°F at sea level	lb/ft^3	0.058

*Condition of He inside Kytoon.

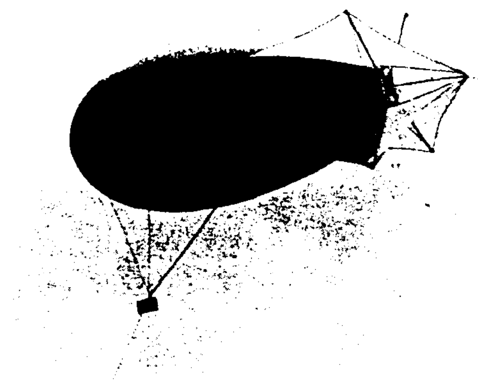

Figure 1. Kytoon in Tethered Flight

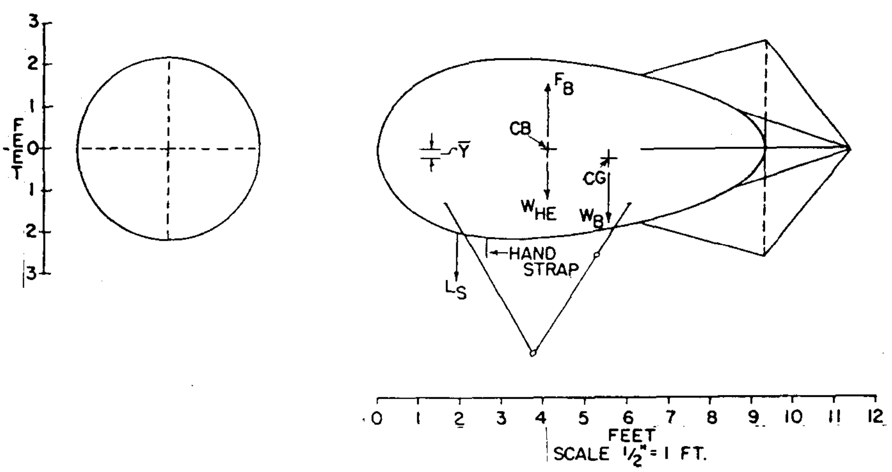

Figure 2. Free Body Diagram of the Kytoon on an Even Keel in Calm Air

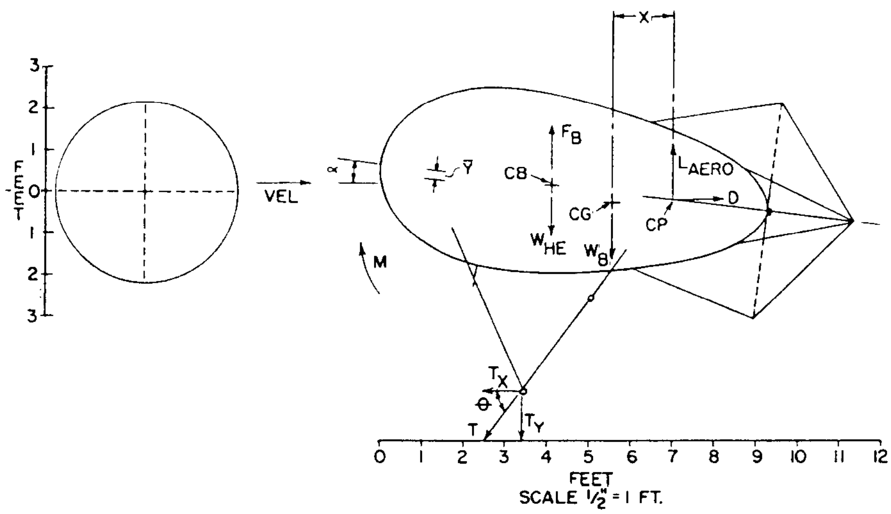

Figure 3. Free Body Diagram of the Kytoon in Tethered Flight

In order to determine the design strength of the tether line, loads on the Kytoon were investigated for the worst possible flight condition in a maximum wind of 30 mph. Since the optimum months for obtaining usable scientific data appeared to be April, May, and June, a statistical analysis was conducted for the winds on Wallops Island for these months (References 6, 7, and 8). From this statistical analysis, it was concluded that the probability was greater than 90 percent that these winds would be less than the design wind of 30 mph. It was found that the worst flight condition was that of a cylinder in cross flow, or that the Kytoon would have an angle of attack of 90°. For the cross-flow condition, the drag force was determined to be 93 lb for the design wind speed. A safety factor of 1.5 was incorporated, giving a minimum design break strength of the tether line of 140 lb.

Since a high strength-to-weight ratio was desired, wire rope, steel wire, and other types of line were eliminated owing to their low strength-to-weight ratio. Two types of line found to have the desired strength-to-weight ratio include twisted and braided nylon. For a given break strength, the twisted nylon was found to be 14 percent lighter than the braided nylon. However, experience has shown the following characteristics of the two types of line:

a. Braided nylon remains straight instead of knotting up in itself as does twisted nylon line when tension is continuously applied and released.

b. Twisted nylon will "friction wear" quicker than braided nylon ("friction wear" - rubbing against itself).

c. Braided nylon acts as a better shock absorber than does twisted nylon due to the variations of their respective spring constants. These spring constants were determined at Wallops Station, utilizing a spring scale and tape rule to measure the force and elongation, respectively.

Based on this experience, 160-lb braided nylon bow string was used as tether line. The tether line was attached to the Kytoon by means of an attach swivel. A modified slip knot, which was experimentally determined to have a knot efficiency factor of greater than 95 (Reference 1), was used to connect the attach swivel to the tether line. The tether line was connected to a 3.5 to 1 hand-operated cable winch assembly, which was used to raise and lower the Kytoon. This winch was modified to be a 1 to 1 hand-operated cable winch in addition to the original 3.5 to 1 hand-operated cable winch. This modification was put into effect in order to reduce the possibility of contamination to the payloads during the raising and lowering of the Kytoon, which takes 10 to 13 min, respectively. The payload consisted of a microscope slide mounted in a pollen trap. The slide has an adhesive area capable of capturing and retaining any airborne particle which may come in contact with it. The pollen trap, as shown in Figure 4, designed and fabricated at Wallops Station, provides a means of suspension for the slide, protecting it from coming in contact with any undesirable airborne particles. Due to weight considerations and possible corrosive reactions, the pollen trap is nonmetallic and covered with a nonmetallic screen of 250 US Standard mesh (Reference 1). The pollen traps weigh approximately 100 grams each.

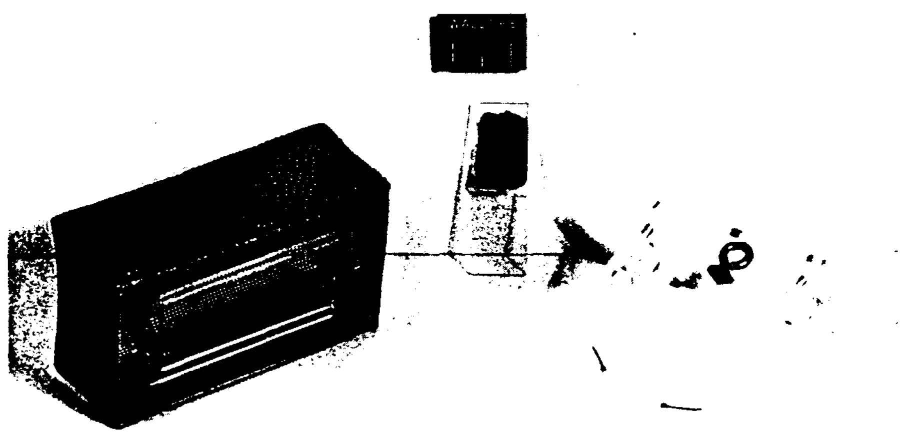

Figure 4. Pollen Trap

In order to prevent the payloads from fraying the tether line, a length of Teflon tubing was added to the tether line at the payload attach points. The Teflon tubing, flared on both ends, was attached directly to the Kytoon attach swivel. When more than one payload was employed, a separate line was attached to the Teflon tubing and followed the tether line until the desired increment of altitude was attained. This payload line was then connected to another section of Teflon tubing, where the additional payload was attached.

The pollen trap was connected to the payload line by a brass 2/0 snap swivel. The snap swivel was used because it provided both a means of attaching the payload and a swivel allowing the payload a limited freedom of movement. Brass hardware was utilized as much as possible owing to its resistance to corrosion.

The project requirements specify maintaining a total of seven pollen traps in 100-ft intervals from altitudes of 400 to 1,000 ft. In order to achieve an altitude of 1,000 ft, a tether line of 1,320 ft is required (Figure 9). From Table 1, the tether line weight was found to be 1.70 lb. Since the total weight of the seven pollen traps is 1.57 lb, the total weight to be sent aloft is 3.27 lb. Table 1 shows that the Kytoon can lift a maximum of 2.134 lb in the absence of any winds. Therefore, it is not feasible for the Kytoon to lift the required weight of 3.27 lb in a calm wind condition. Since one Kytoon would not meet the project requirements, two alternatives were investigated: (1) to put two or more Kytoons in tandem, and (2) to utilize several independent single Kytoon systems. The tandem arrangement was found to be impractical because of the following:

a. As the distance between two cylinders decreases less than 0.9, the maximum diameter of one of the bodies, the drag force increases. When these two bodies are in contact with each other, as is the case of two Kytoons being flown in tandem, the drag force for the two Kytoons would be approximately three times greater than the drag force on a single Kytoon (Reference 3).

b. When two Kytoons are in a tandem arrangement, the necessary tether line weight is increased, owing to greater tensile strength requirement, by a factor of 2.4 times greater than that required for the single Kytoon system. This tether line weight, when added to the weight of the pollen traps, is 1.4 lb greater than static lift of the two Kytoons in a tandem arrangement.

However, three independent single Kytoon systems will meet the project requirements, as shown in Table 4:

Table 4. Three Independent Single Kytoon Systems

System No.	No. of Pollen Traps	Total Amount of Weight Sent Aloft Per System (lb)	Percent of Additional Free Lift	Altitude of Kytoon (ft)
1	1	1.98	16	1,000
2	2	1.91	16	900
3	4	1.87	19	700

These three systems were arranged so that there would be a minimum chance of their respective tether lines becoming entangled with each other (see Figure 5). The south end of Wallops Island was chosen as the tether site because there were no buildings, power and telephone lines, or other obstacles with which the tether line might become entangled.

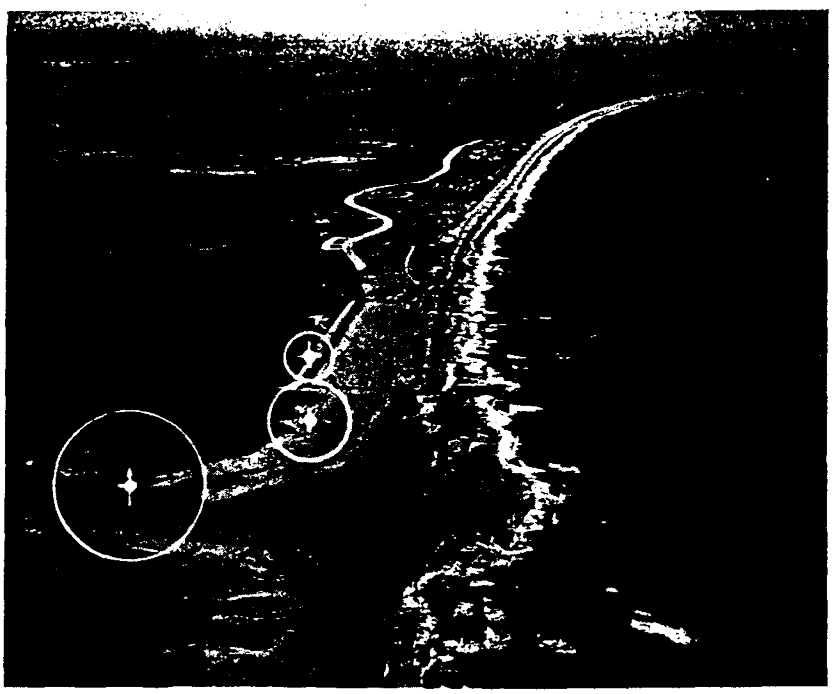

Figure 5. South End of Wallops Island Looking North

4. PERFORMANCE (STATIC AND DYNAMIC ANALYSIS)

4.1 Static Analysis

The volume of helium used to inflate the Kytoon to have a calm air usable free lift of 964 grams was found in two ways, both of which were in close agreement. The method of slicing, which is an approximate method to determine the volume of a body is given by

$$V = \sum_{0}^{\ell} A(x) \Delta x$$

and was found to be 87.791 cu ft. As $|\Delta x|$ becomes smaller, the approximation of the volume approaches the exact volume. The second method was to find the volume of a solid generated by rotating a plane area about an axis; this is called a solid of revolution. To find the volume of a solid $A(x)$ of a circle whose radius $r = y = f(x) = 0.6696 + 0.7132x - 0.0823x^2$ so that

$$\begin{aligned} A(x) &= \pi r^2 \\ &= \pi [f(x)]^2 \\ &= \pi y^2 \\ V &= \int_0^{\ell} A(x)\, dx \\ &= 86.044 \text{ cu ft} \end{aligned}$$

The center of gravity (c.g.) of the Kytoon was found (see Figures 2 and 3). The buoyancy due to the helium has a resultant force F_B which acts vertically upward at the center of volume of the enclosed gas or the center of buoyancy (c.b.). According to Archimedes' principle, the buoyant force F_B for a body submerged in a fluid is equal to the weight of the fluid displaced by the body. Since the Kytoon is submerged in air, and it was assumed that the displaced volume of air is not compressed, the buoyant force is given by

$$F_B = \gamma_A V_A$$

where

$$\gamma = \frac{P_A}{R_A T_A}$$

The weight of helium was found in a similar manner, and since the weight of the uninflated Kytoon is known, the usable free lift, L_s, is determined by

$$\uparrow \Sigma F_Y = 0$$

and is shown in Figure 2. The usable free lift was computed to be 2.677 lb. However, for the measured volume of helium, the usable free lift was measured to be 2.13 lb. This difference is attributed to the fact that the actual pressure and temperature of air were slightly higher than standard sea level pressure and temperature and the internal pressure of the helium was somewhat different from the value which was assumed. The usable free lift is defined as the force necessary to hold the inflated airship in an equilibrium condition in calm air. The weight of the payload and attached hardware must be subtracted from the usable free lift.

4.2 Dynamic Analysis

When the Kytoon is exposed to a wind velocity, aerodynamic forces, such as aerodynamic lift and drag, must be considered. The resultant force exerted by the moving air on the tethered Kytoon due to the normal (pressure) and tangential (frictional) stresses will have a horizontal component D and a vertical component L_{Aero}. These are parallel and perpendicular to the direction of the wind velocity vector, v, respectively, and are assumed to act at the center of pressure (c.p.). These are shown in Figure 3 with the Kytoon assuming an angle of attack, α.

Tests conducted at Wallops Island showed that the Kytoon, when tethered in a wind velocity of 12 mph, has a pitch angle of attack $\alpha = 7.5°$ and a yaw angle of attack $\beta = 0°$. The pitch angle of attack was measured using a modified Model K-110-1 clinometer, whereas the yaw angle of attack was measured with a specially constructed beta gage.

As shown in Figure 3, the components of the tether line tension, T, are related to the total lift and drag forces of the Kytoon. The tension of the tether line is given by

$$\vec{T} = L_{\vec{T}} + \vec{D}.$$

When the Kytoon is in an equilibrium condition, the horizontal and vertical components of the tether line tension may be found by

$$\rightarrow \Sigma F_X = 0 = D - T_x$$

$$\uparrow \Sigma F_y = 0 = F_B - W_{He} + L_{Aero} - W_B - T_y$$

The aerodynamic drag on the tether line was computed and found to be negligible. The aerodynamic pitching moment, M, is found by

$$M_{c.g.} = \left(F_B - W_{He}\right)(1.49) - L_{Aero}\, x + T_x (4.6) - T_y (1.82) - D\left(x \tan^{\alpha} - \frac{\bar{y}}{\cos^{\alpha}}\right)$$

This resultant moment must be equal to zero when the tethered Kytoon is in a condition of equilibrium. The tether line tension and tether angle were measured on Wallops Station and the aerodynamic lift and drag forces were computed. From the aerodynamic lift and drag forces, the lift and drag coefficients were determined (see Figure 6). It is noted from the lift coefficient data that this system realizes a total lifting capability of 4.5 lb in a steady 15 mph wind. The tether line tension and tether angle were measured using a spring scale and a Model K-110-1 clinometer, respectively. The wind velocity, experienced by the Kytoon, was measured using a hand-held anemometer. Prior to these tests, the anemometer was checked

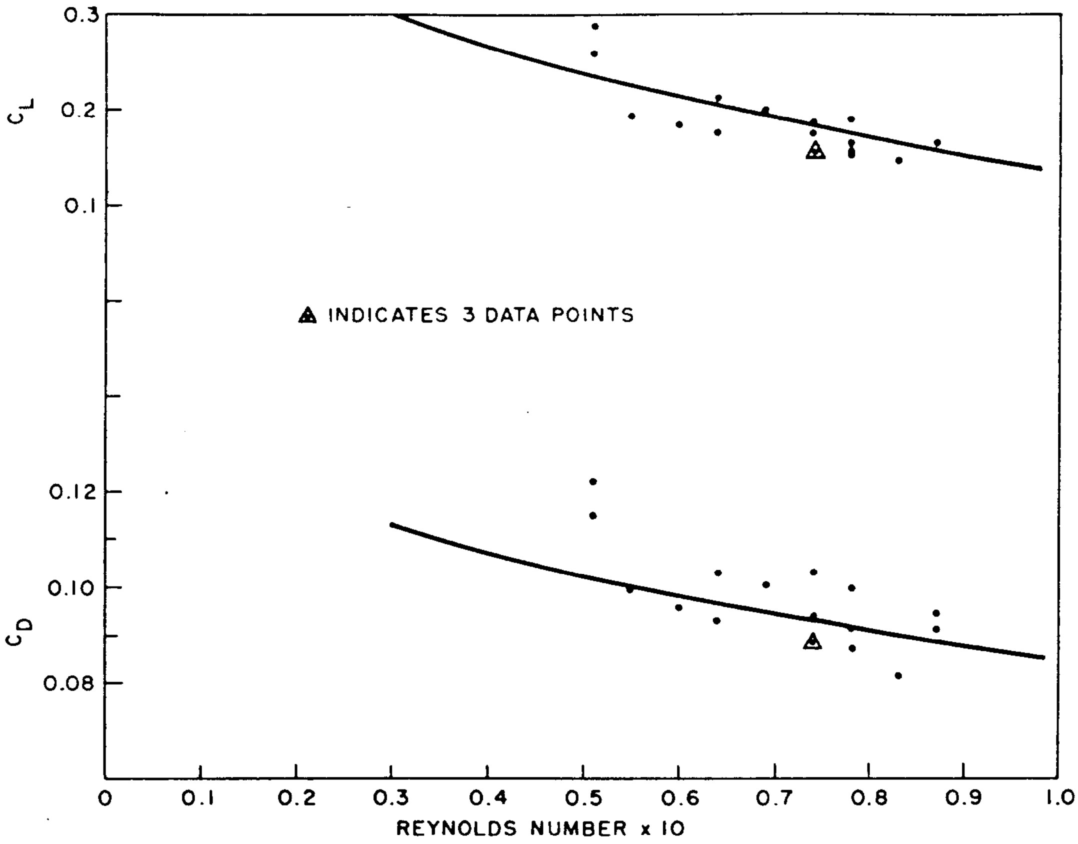

Figure 6. C_D and C_L vs Reynolds Number for the Kytoon. $R_N = \frac{\rho \, d_{max} \, v}{\mu}$

for accuracy and found to be in a calibrated condition. The tether angle, θ, versus wind speed is shown in Figure 7. The Reynolds number for the Kytoon was computed and is shown versus wind velocity in Figure 8. Figure 9 is a plot of measured tether line length versus Kytoon altitude for an average wind velocity of 12 mph. This test was conducted on Wallops Island and the data were acquired by the FPS-16 radar. Figure 10 presents smoothed radar data (FPQ-6) showing typical variations of altitude for a period of 200 sec, chosen at random, for the Kytoon in tethered flight. It is noted from this figure that the maximum change in altitude over this time period is approximately 8 percent. There was no instrumentation available to measure the local wind conditions during this period of flight.

Flight testing of this system revealed that when the Kytoon senses a steady wind velocity of 21 mph, it begins to undulate. As the steady wind velocity increases past 21 mph, this undulation becomes more violent. This dynamic behavior was experienced in repeated tests. A quantitative explanation for this behavior is not offered.

It is noted that this motion begins at a Reynolds number of approximately 1×10^6 and that this is a region of transition for similar bodies of revolution.

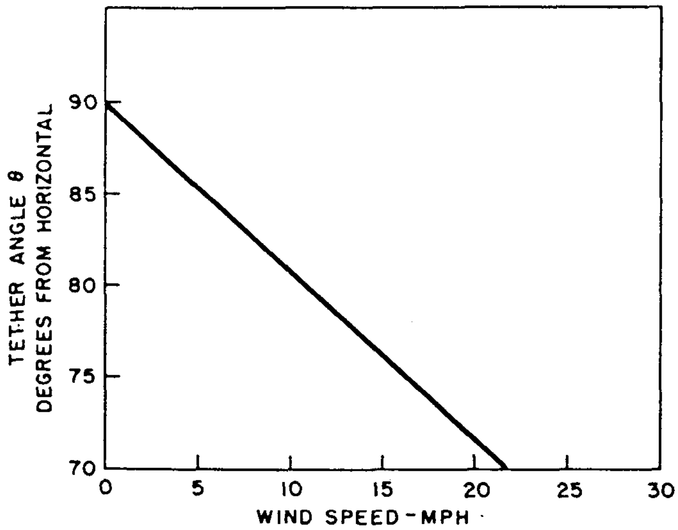

Figure 7. Tether Angle vs Wind Velocity for the Kytoon

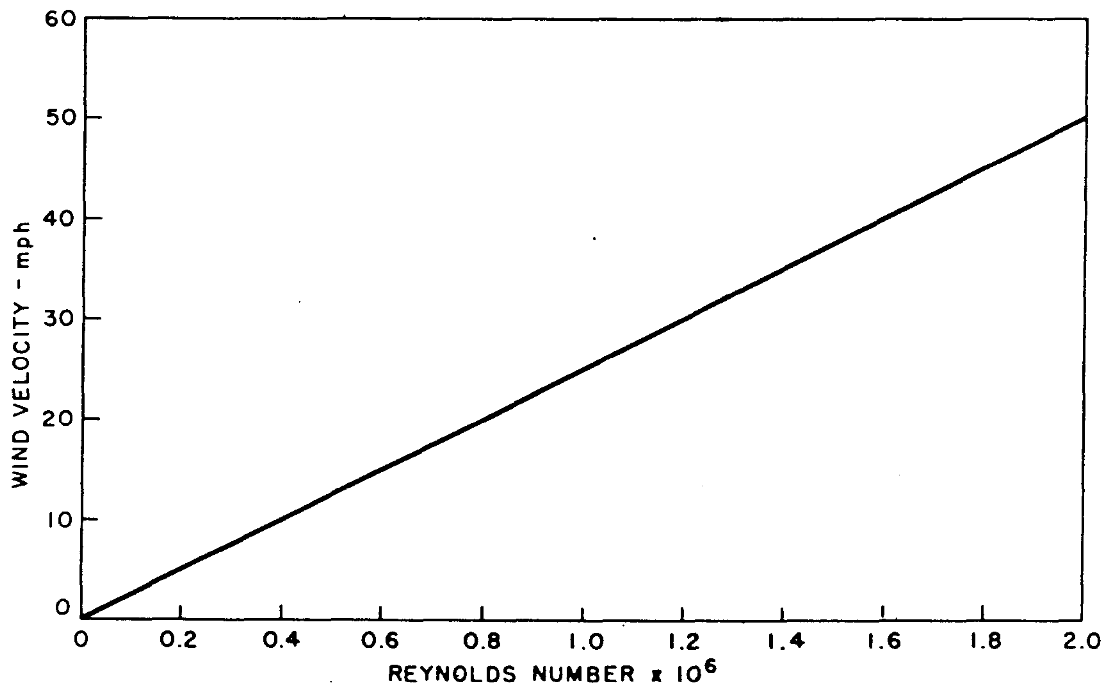

Figure 8. Wind Velocity vs Reynolds Number for the Kytoon. $R_N = \frac{\rho\, d_{max}\, v}{\mu}$

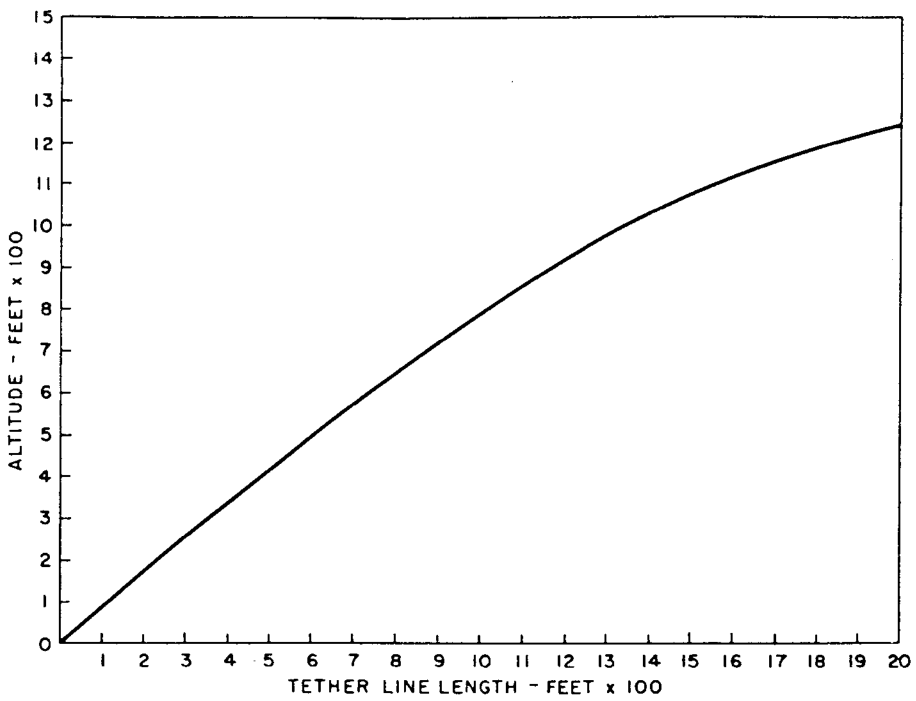

Figure 9. Altitude vs Kytoon Tether Line Length. Average wind velocity = 12 mph

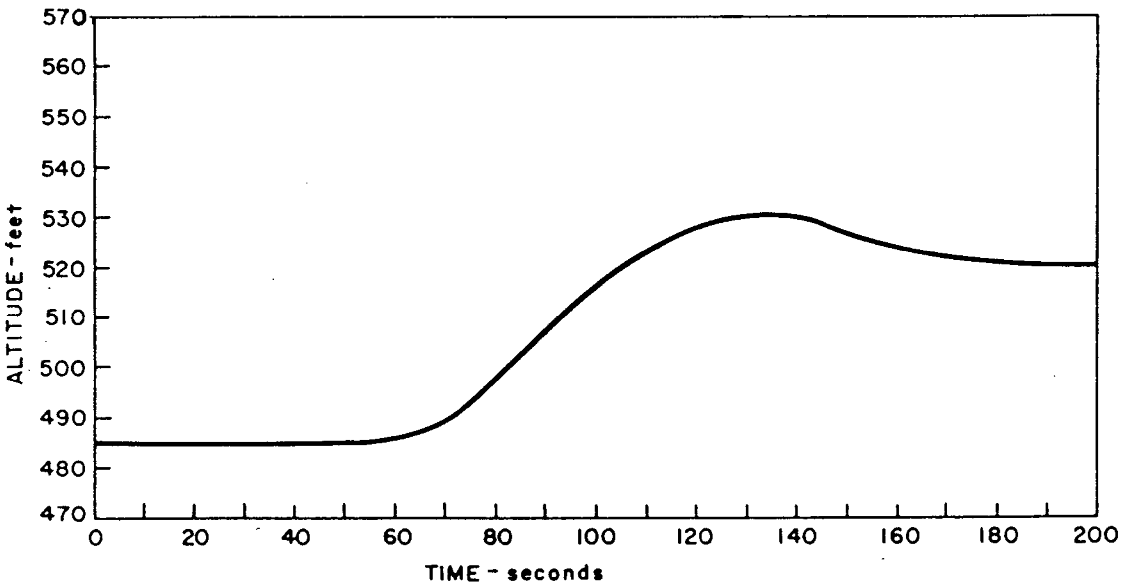

Figure 10. Altitude vs Time - Kytoon in Tethered Flight

5. OPERATIONAL EVALUATION

The Kytoon, as initially received from the manufacturer, did not prove satisfactory for prolonged tethered flight. It appeared that the nylon casing at the rear of the Kytoon would pull itself through the rear assembly tail plate, transmitting the fin loads directly to the neoprene bladder, causing it to become ruptured at its weakest point. Because of this basic design problem, the Kytoon was modified by attaching four tabs to the rear section of the nylon casing. When the tail assembly struts were placed through these tabs, the nylon casing was retained in its original position, causing the fin loads to be transmitted to the nylon casing rather than to the bladder. Since the Kytoon is not steady when totally restrained at the surface in gusty winds or winds greater than 10 to 12 knots, it is required that Kytoon inflation take place in a sheltered area. Due to its vulnerability in these winds, it was ascertained that the optimum time to send the Kytoon aloft is when winds are at their minimum speed, which usually occurs at dawn and dusk. Because there was not a sheltered area available at the tether site, the Kytoon was inflated in the Weather Bureau balloon inflation area and transported to the tether point. It takes two men approximately one hour to transport an inflated Kytoon from the inflation area to the tether point, attach the payload, send it aloft, and return to the inflation area. Approximately one hour is required by one man to change the bladder in the Kytoon and put it in a flight-ready condition provided that it is done in a sheltered area. Since the life expectancy of the neoprene bladder was found to be 12 hours of constant exposure to sunlight, the bladder should be changed after a 24-hour period of tethered flight, of which no more than 12 hours should be during the daylight hours. This condition was for a Kytoon with a high degree of thermal reflectivity. It was not determined what the life expectancy of the bladder would be if the Kytoon were to act as a "black body."

Due to the permeability of the gas envelope to helium, approximately 15 percent of the usable free lift is lost in a 24-hour period. In view of this loss of free lift, it was determined that, by over-inflating the Kytoon at dusk, it could remain aloft for a 24-hour period (the amount of overinflation being the amount necessary to compensate for the loss of usable free lift during the first 12-hour period of tethered flight). It is felt, however, that the Kytoon, which has remained aloft overnight, be inspected after 12 hours of flight in the event that maintenance may be required.

Prior to sending the Kytoon aloft, certain requirements of the Federal Aviation Agency (FAA) had to be met and special meteorological data and forecasts had to be obtained and evaluated. The FAA requirements were imposed in order to minimize the potential hazard to aircraft in the event that the flight condition of the Kytoon should change from tethered to free flight. Since the volume of the Kytoon is less than 115 cu ft and its maximum diameter is less than 6 ft, the FAA regulations did not apply to the Kytoon itself, but to the payload which it carried (Reference 5). These requirements imposed by the FAA include the following:

a. Notification prior to sending the Kytoon aloft, expected time and position of flight, and a general description of the system.

b. Verification of position at least once every 2 hours on a continuous basis.

c. Notification of the nearest FAA Air Traffic Control facility in the event that the Kytoon was to achieve a free flight condition.

During the times of operation of the Wallops range, the time and position of flight were recorded by the Island Radar Section. The data obtained from radar were later reduced and used for data correlation. During the times that the radar facility was not available, the Wallops Damage Control Section would visually ascertain that the Kytoon was still in a tethered flight condition. A procedure was inaugurated to notify the FAA if it were deemed necessary.

The meteorological data and forecasts involved included the following:

a. The probability that thundershower activity would interfere with normal flight conditions.

b. Special forecasts for winds in the realm of flight.

During the times of operation of the Wallops range, these data were obtained from the Wallops Station forecast office. When the forecast office was not in operation, provisions were made to obtain the necessary meteorological data from another forecast office, which was evaluated by the writer when coupled with local conditions. If the probability was 30 percent or greater that undesirable weather conditions would occur, the Kytoon was grounded and placed in a shelter for the forecast period. In the event that these undesirable weather conditions occurred without any prior forecast, the writer was notified so that the tethered Kytoons could be grounded and placed in a shelter as soon as possible. For the period beginning at 1700Q, 3 June 1966, and ending at 0800Q, 22 June 1966, there were 37 12-hour periods of possible flight for the Kytoon systems. Of these 37 12-hour periods, 25 were cancelled owing to either a forecast of adverse weather conditions or actual adverse weather conditions that were not predicted. This represents 67 percent of the total possible time of operation.

6. CONCLUSION

The Kytoon system as configured and operationally deployed in this initial phase of the Aeropalynological Survey is capable of obtaining useful scientific data. However, the performance capabilities and operational characteristics of the Kytoon system have been demonstrated and found to be limited and not suitable as an operational tool for the Aeropalynologic Survey Project.

References

1. Baumeister, Theodore (1958) Marks' Mechanical Engineers Handbook, 6th ed., McGraw-Hill, New York.
2. Brown, Aubrey I., and Marco, Salvatore M. (1958) Introduction to Heat Transfer, 3d ed., McGraw-Hill, New York.
3. Horner, Sighard F. (1958) Fluid Dynamic Drag, published by the author, Midland Park, New Jersey.
4. How to Assemble and Fly Dewey and Almy Kytoon, Dewey and Almy brochure.
5. Moored Balloons, Kites, and Unmanned Rockets and Unmanned Free Balloons (1964) Federal Aviation Regulation, Part 101, Government Printing Office, Washington, D.C.
6. U.S. Dept. of Commerce, Winds Aloft and Summary Parameter Wallops Island, Virginia, April 1965, Weather Bureau, National Weather Records Center, Asheville, North Carolina.
7. U.S. Dept. of Commerce, Winds Aloft and Summary Parameter Wallops Island, Virginia, May 1965, Weather Bureau, National Weather Records Center, Asheville, North Carolina.
8. U.S. Dept. of Commerce, Winds Aloft and Summary Parameter Wallops Island, Virginia, June 1965, Weather Bureau, National Weather Records Center, Asheville, North Carolina.

Symbols

d	diameter	ft
d_{max}	maximum diameter	ft
ℓ	length	ft
f	fineness ratio $\frac{\ell}{d_{max}}$	
V	volume $\int_0^{\ell} A(x)\,dx$	ft^3
R_N	Reynolds number $\frac{\rho\, d_{max}\, v}{\mu}$	
v	velocity	fps
ρ	density	$slugs/ft^3$
μ	viscosity	$\# sec/ft^2$
F_B	total buoyant force $\gamma_A V_A$	lb
γ	specific weight $\frac{P}{RT}$	$\#/ft^3$
R	universal gas constant	ft/°R
°T	temperature	°R

Symbols

P	pressure	psf
L_s	static or usable free lift	lb
L_{Aero}	aerodynamic lift $C_L qS$	lb
L_T	total lift $L_s + L_{Aero}$	lb
D	aerodynamic drag $C_D qS$	lb
S	aerodynamic reference area $V^{2/3}$	ft^2
α	pitch angle of attack	deg
β	yaw angle of attack	deg
C_L	aerodynamic lift coefficient	
C_D	aerodynamic drag coefficient	
q	dynamic pressure $1/2\ \rho\ V^2$	psf
T	tether line tension	lb
W	weight	lb
M	aerodynamic pitching moment	ft-lb
c.b.	center of buoyancy	
c.g.	center of gravity	
c.p.	center of pressure	
A (subscript)	air	
B (subscript)	balloon	
He (subscript)	helium	